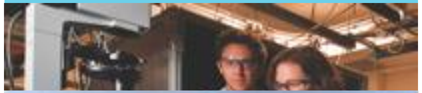
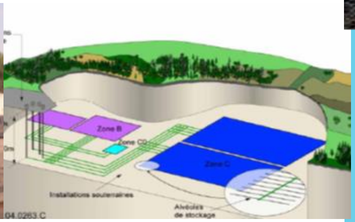
Geologic Disposal of High Activity Radioactive Waste, Waste Forms, and Waste Streams: Considerations for Disposal





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Outline

- Disposal concepts
- Waste characteristics affecting disposal
- How alternative nuclear fuel cycles might change waste forms requiring deep geologic disposal
- How existing safety assessments inform observations about the impacts of such changes on repository performance (examples from multiple programs)
- Open questions and R&D
- Conclusions

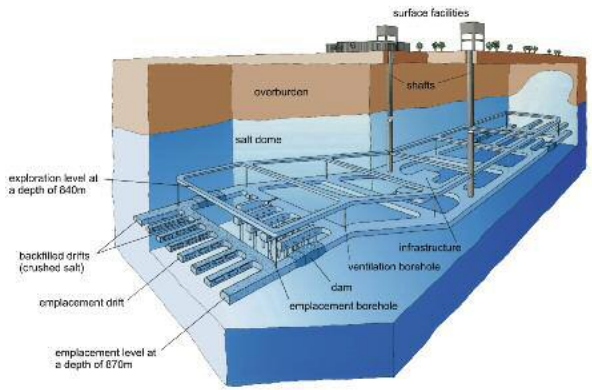
Deep Geological Disposal for Spent Nuclear Fuel and High-Level Radioactive Waste

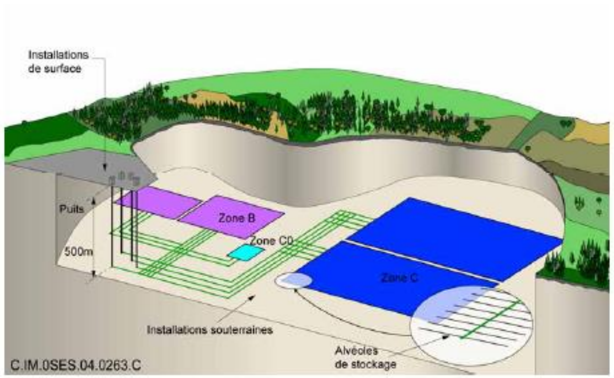
Deep geologic disposal has been planned since the 1950s

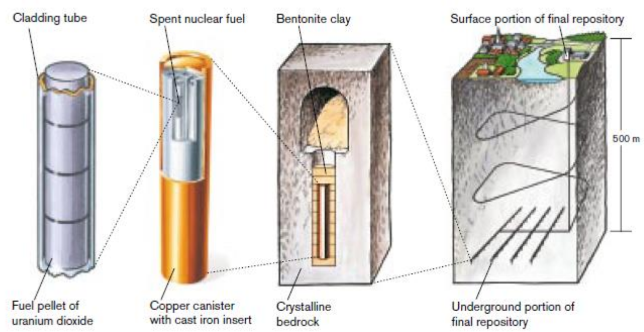
"There has been, for decades, a worldwide consensus in the nuclear technical community for disposal through geological isolation of high-level waste (HLW), including spent nuclear fuel (SNF)."

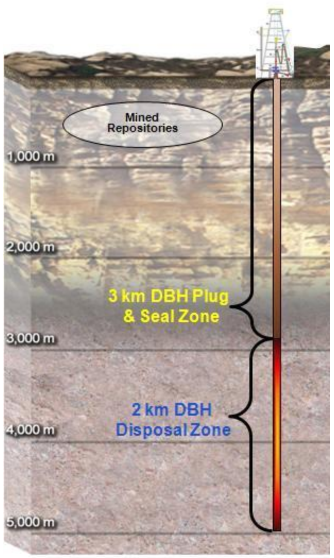
"Geological disposal remains the only long-term solution available."

National Research Council, 2001









Status of Deep Geologic Disposal Programs World-Wide

Nation	Host Rock	Status
Finland	Granitic Gneiss	Construction license granted 2015. Start of final disposal planned for mid -2020s
Sweden	Granite	License application submitted 2011 Local municipalities gave approval Oct. 2020 Construction planned to start in mid-2020s
France	Argillite	Disposal operations planned for 2025
Canada	Granite, sedimentary rock	Candidate sites being identified
China	Granite	Repository proposed in 2050
Russia	Granite, gneiss	Licensing planned for 2029
Germany	Salt, other	Uncertain
USA	Salt (transuranic waste at the Waste Isolation Pilot Plant) Volcanic Tuff (Yucca Mountain)	WIPP: operating Yucca Mountain: suspended
Japan	TBD	Candidate sites being identified
Korea	TBD	Candidate sites being identified

Others: Belgium (clay), UK (uncertain), Spain (uncertain), Switzerland (clay), Czech Republic (granitic rock), all nations with nuclear power.

Sources: Faybishenko et al. 2016; World Nuclear News 2020; Posiva Oy 2019; ABC News 2020; Wiley Online Library 2020

How Repositories Work

Natural barriers prevent or delay water from reaching waste form

Engineered barriers prevent or delay water from reaching waste form

Slow degradation of waste form limits exposure to water

Near Field: water chemistry limits aqueous concentrations

Natural and engineered barriers prevent or delay transport of radionuclides to the human environment

Overall performance relies on multiple components; different disposal concepts emphasize different barriers

Time (radioactive decay)

Isolation mechanisms may differ for different nuclides in different disposal concepts

Technical Characteristics/Properties of Waste Forms to be Considered for Disposal Strategy

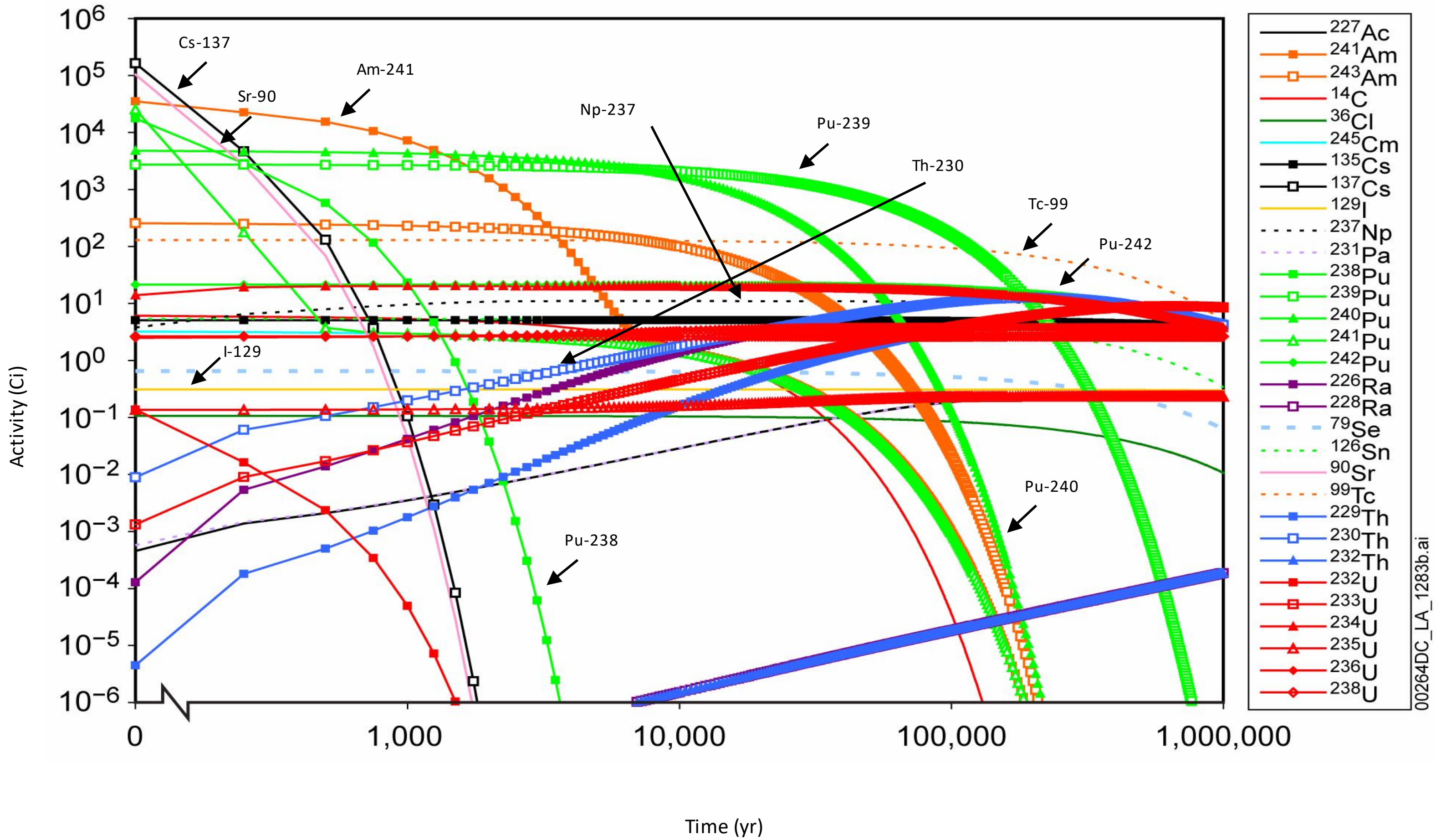
- Waste forms should be disposable in any of the possible generic geologic disposal concepts
  - Not striving to optimize waste forms and disposal geologies
- Potential for criticality over repository time scales (e.g., CSNF in DPCs)
  - Current SNF dry storage canisters designed to prevent criticality over timescales commensurate with storage and transport, not disposal
  - DOE investigating the consequences of postclosure criticality on repository performance
- Thermal output per waste package (e.g., CSNF in DPCs)
  - Thermal limits per waste package vary by repository concept: geologic media and repository design
  - Options include repackaging, long-term above-ground storage, spacing of waste packages and drifts
- Whether it is vigorously reactive to water (e.g., Na-bonded spent fuel)
- Waste form degradation rate (e.g., salt waste)
- Rate of gas generation (e.g., fluoride-based salt from MSR)

How Might Alternative Nuclear Fuel Cycles Impact Geological Disposal?

- For a given amount of electric power, alternative fission-based nuclear fuel cycles may result in:
  - Changes in the radionuclide inventory
    - *Reprocessing can reduce actinide content of final waste product*
    - *Actinides not always largest contributor to dose*
  - Changes in the volume of waste
    - *Reprocessing can reduce the volume of waste requiring deep geologic disposal*
    - *Cost of disposal not necessarily reduced significantly*
  - Changes in the thermal power of the waste
    - *Separation of minor actinides can reduce thermal power of the final waste form*
    - *Fission products are the major contributor to thermal power in first century*
  - Changes in the durability of the waste in repository environments
    - *Treatment of waste streams can create more durable waste forms*
    - *More durable waste form desirable for all disposal geologies*
- For each potential change, consider
  - How will these changes impact repository safety?
  - How will these changes impact repository cost and efficiency?

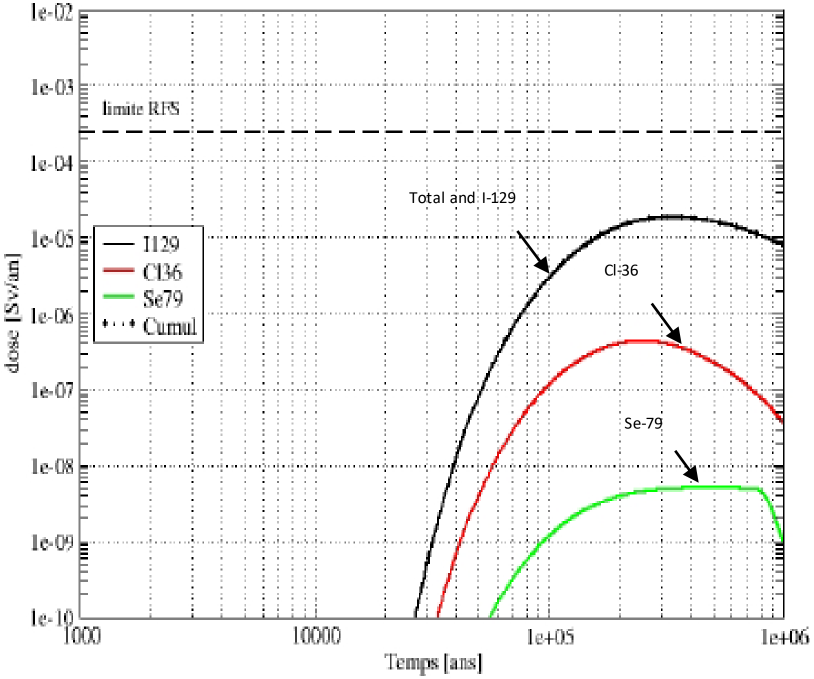
Light-Water Reactor Spent Nuclear Fuel Activity

Example from US Program



DOE/RW-0573 Rev 0, Figure 2.3.7-11, inventory decay shown for a single representative Yucca Mountain spent fuel waste package, as used in the Yucca Mountain License Application, time shown in years after 2117.

Contributors to Total Dose: Meuse / Haute Marne Site (France)

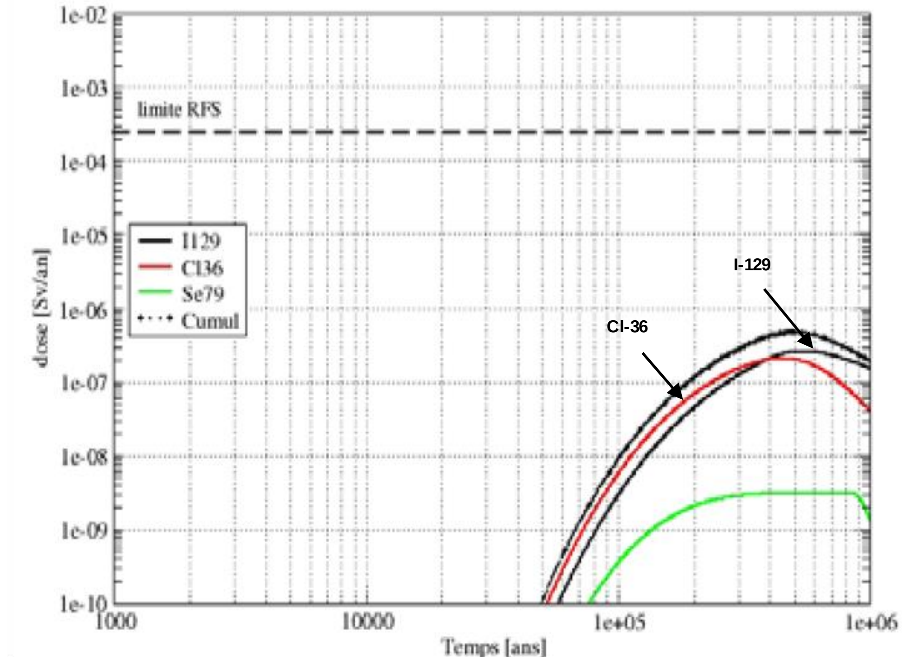


ANDRA 2005, Figure 5.5-18, million year model for spent nuclear fuel disposal and Figure 5.5-22, million year model for vitrified waste disposal

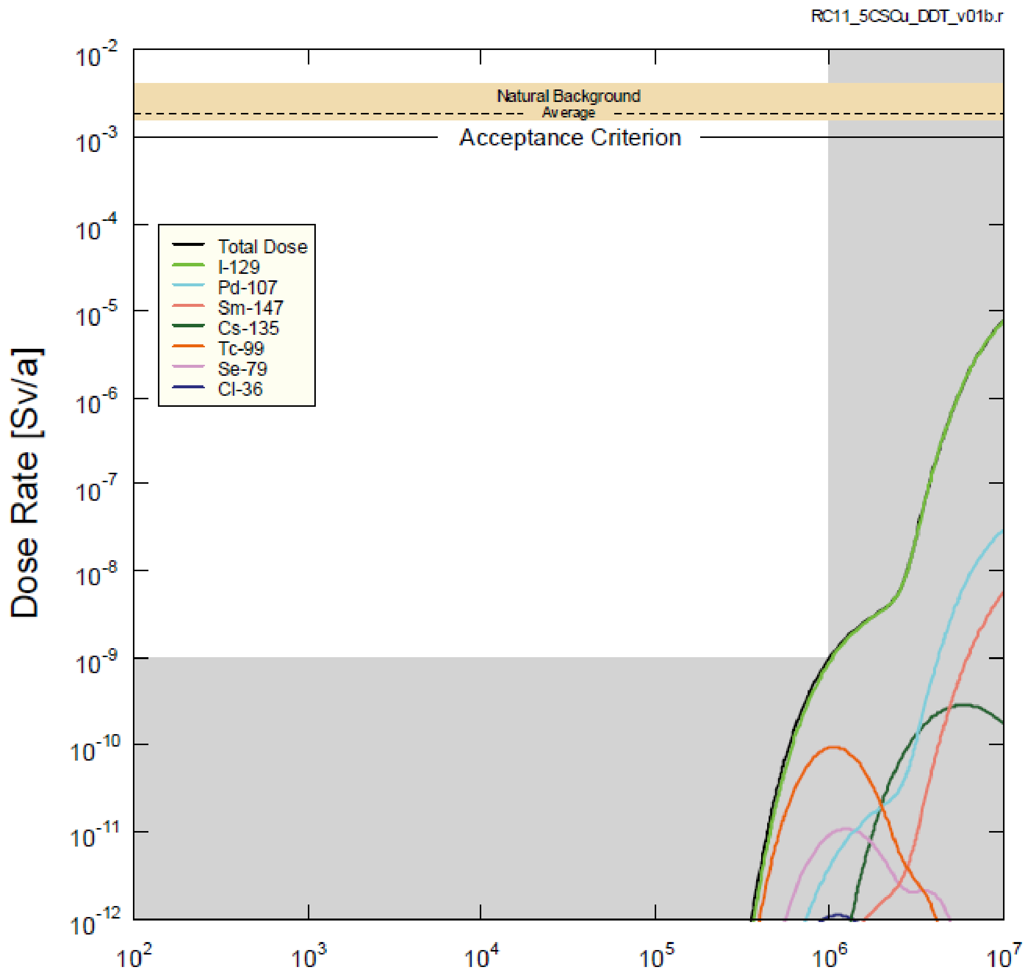
Diffusion-dominated disposal concept: Argillite

I-129 is the dominant contributor at peak dose

Examples shown for direct disposal of spent fuel (left) and vitrified waste (below)



Contributors to Total Dose: Hypothetical Site (Canada)



NWMO 2013, Figure 7-96.

Diffusion-dominated disposal concept: spent fuel disposal in unfractured carbonate host rock

Long-lived copper waste packages and long diffusive transport path

All waste packages assumed to fail at 60,000 years for this simulation; primary barriers are slow dissolution of SNF and long diffusion paths

Major contributor to peak dose is I-129

Contributors to Total Dose: Forsmark site (Sweden)

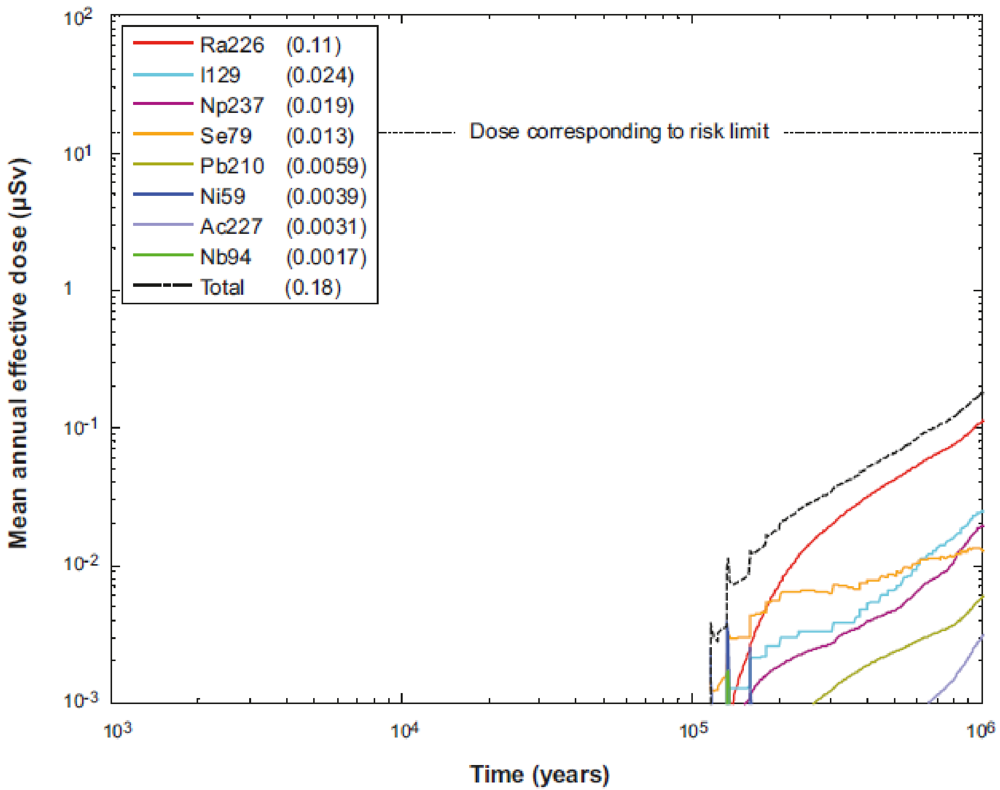


Figure 13-18. Far-field mean annual effective dose for the same case as in Figure 13-17. The legends are sorted according to descending peak mean annual effective dose over one million years (given in brackets in µSv).

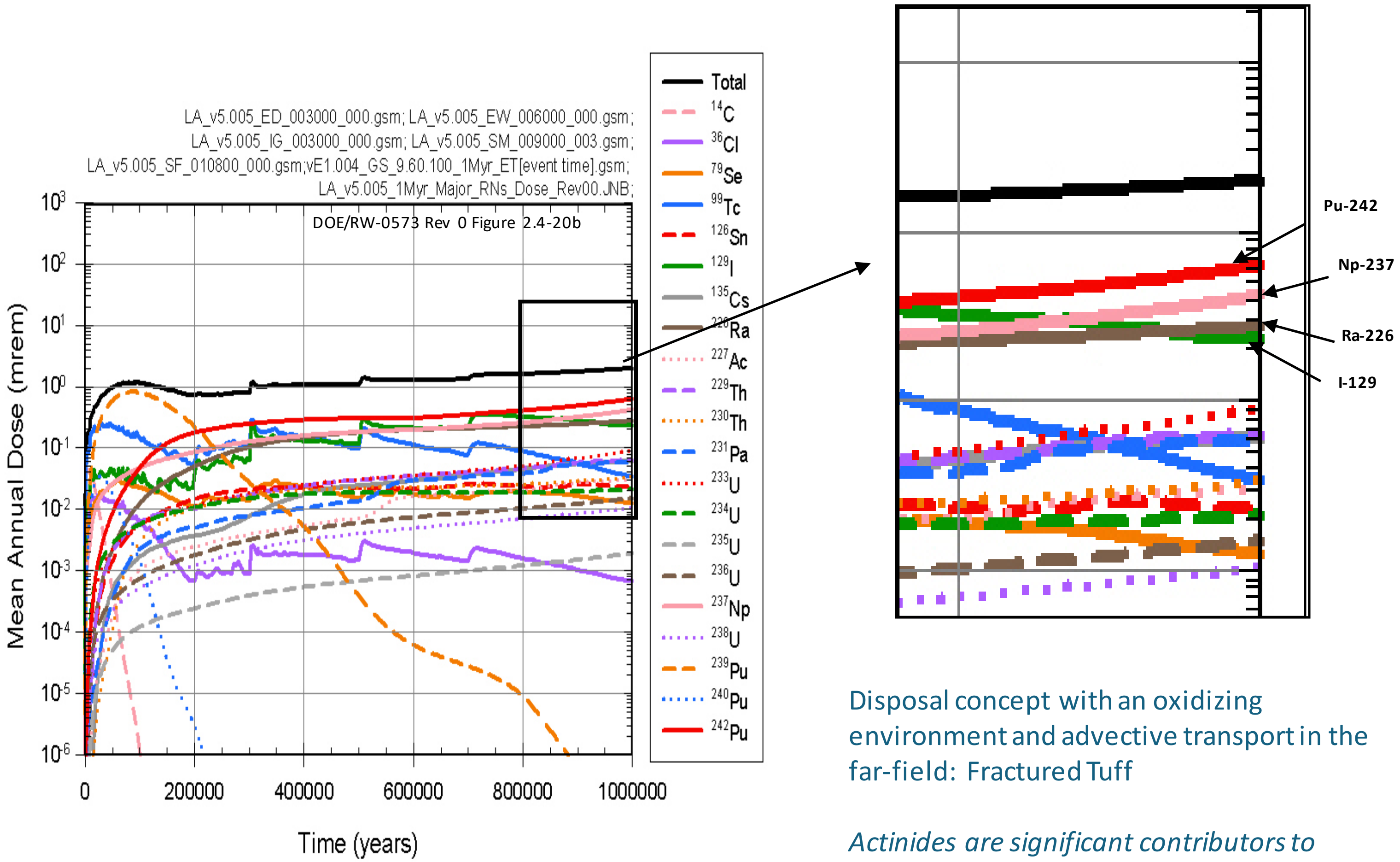
SKB 2011

Disposal concept with advective fracture transport in the far-field: Granite

Long-term peak dose dominated by Ra-226

Once waste packages fail via corrosion, dose is primarily controlled by fuel dissolution and diffusion through buffer rather than far-field retardation

Contributors to Total Dose: Yucca Mountain (USA)

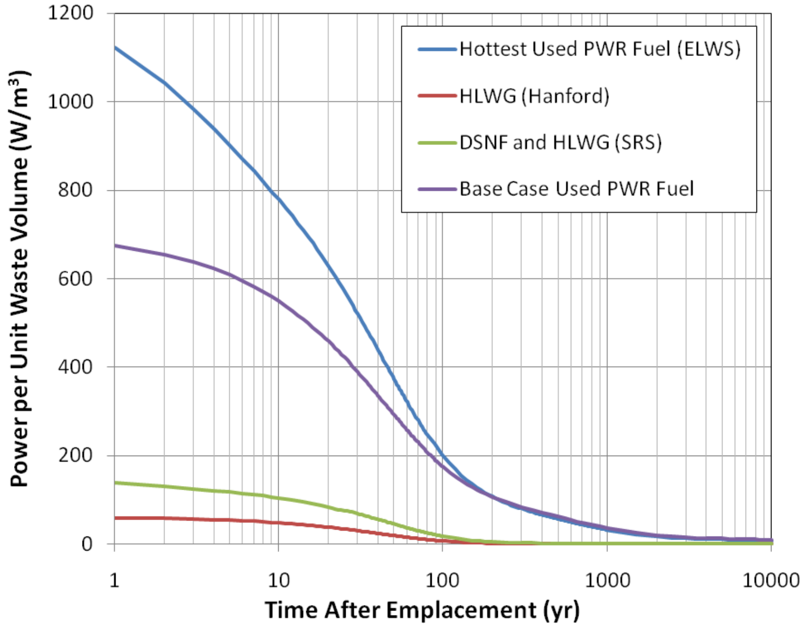


Disposal concept with an oxidizing environment and advective transport in the far-field: Fractured Tuff

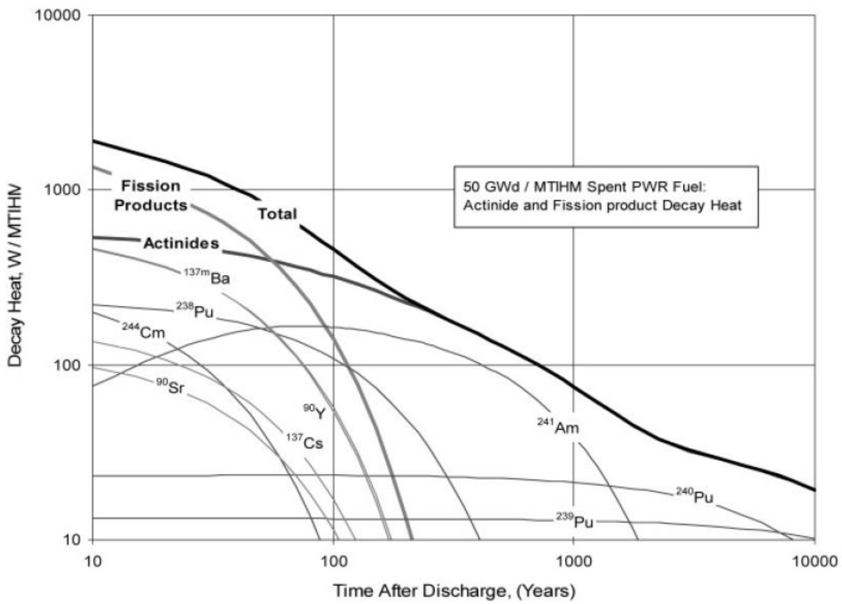
Actinides are significant contributors to dose; I-129 is approx. 1/10th of total

Waste Volume and Thermal Power Considerations

- Repository thermal constraints are design-specific
- Options for meeting thermal constraints include
  - Design choices including size and spacing of waste packages
  - Operational practices including aging and ventilation
  - Modifications to waste forms



Calculated thermal power density vs. time for representative Yucca Mountain waste forms (from Swift et al., 2010, figure 1)



Thermal decay of light water reactor spent nuclear fuel (from Wigeland et al., 2006, Figure 1)

Selection of optimal volume and thermal loading criteria will depend on multiple factors evaluated across entire fuel cycle, including cost and operational efficiency

Waste Volume and Thermal Power Considerations (cont.)

- To a first approximation, waste volume and thermal power density have an inverse correlation without separation of heat-generating radionuclides
  - All other factors held constant, reductions in volume increase thermal power density
  - Relevant metric is disposal volume, i.e., the excavated volume needed per unit volume of waste, which is a function of repository design as well as waste properties
- Volume of HLW is process-dependent
  - Existing processes can achieve substantial reductions in disposal volume
    - Reduction of 60-70% of disposal volume relative to spent fuel (including packaging)
    - Reduction of 92% of disposal volume with Cs removal and 100-yr aging period prior to Cs disposal (von Lensa et al., 2008)
  - Advanced processes may achieve lower volumes of HLW
- Thermal power density of HLW can be engineered over a wide range
- Waste volume does not correlate to long-term performance
  - It does affect cost (excavated volume, total number of repositories); effect is not linear
  - Volume of low-level waste also contributes to total cost

Waste Form Durability Example: Meuse / Haute Marne Site

- HLW
  - Base case model: glass "release periods on the order of a few hundred thousand years" (degradation rate decreases when surrounding medium is saturated in silica: Andra 2005, p. 221)
  - Sensitivity analysis assuming rapid degradation (100s to 1000s of yr) accelerates peak concentrations at outlet by ~200 kyr, modest increase in magnitude of modeled peak dose
    - For rapid degradation case, modeled releases are controlled by diffusive transport time in clay

	Maximum molar flow exiting Callovo-Oxfordian (mol/yr) and maximum dates (yrs.)	
	Reference	Sensitivity
^{129}I	$8.6.10^{-4}$ 460,000 yrs	$9.1.10^{-4}$ 250,000 yrs
^{36}Cl	$2.2.10^{-4}$ 380,000 yrs	$3.8.10^{-4}$ 190,000 yrs

Table 5.5-24 SEN - Attenuation ^{129}I and ^{36}Cl – C1+C2 – comparison between the models $V_0.S$ (sensitivity) and the model $V_0.S \rightarrow V_r$

Impact of changes in HLW glass degradation rate on modeled radionuclide concentrations in groundwater, ANDRA 2005 Table 5.5-24

Waste Form Lifetime Examples: Forsmark Site

- Used fuel
  - Fractional dissolution rate range 10^{-6}/yr to 10^{-8}/yr
    - Corresponding fuel lifetimes: ~ 1 Myr to 100 Myr
    - Dissolution rates for oxidizing conditions (not anticipated), up to 10^{-4}/yr
  - Uncertainty in fuel dissolution rate can be a dominant contributor to uncertainty in modeled total dose estimates for sites with relatively rapid transport

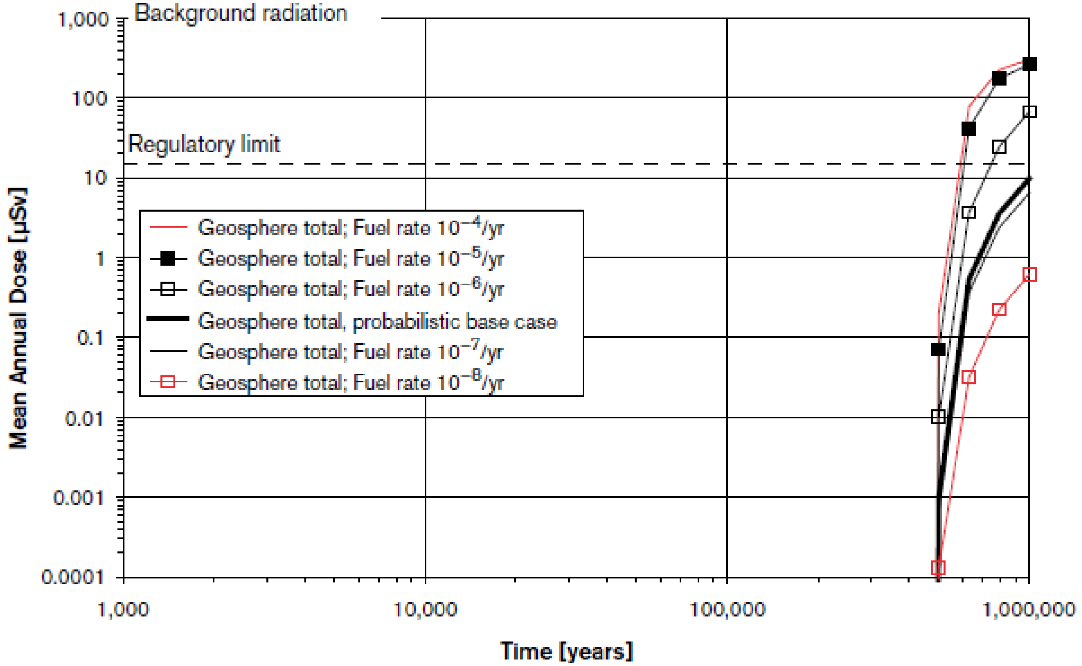


Figure 10-44. Sensitivity of the base case result to the fuel dissolution rate. Semi-correlated hydrogeological DFN model for Forsmark. 1,000 realisations of the analytic model for each case.

Source: SKB 2006, *Long-term Safety for KBS-3 Repositories at Forsmark and Laxemar—a First Evaluation,* TR-06-09, section 10.6.5

Also, SKB 2006, *Fuel and Canister Process Report for the Safety Assessment SR-Can,* TR-06-22, section 2.5.5

ARPA-E WORKSHOP, DECEMBER 2020

Current Status of the US Program

2008	Yucca Mountain Repository License Application submitted
2009	Department of Energy (DOE) determines Yucca Mountain to be unworkable
2010	Last year of funding for Yucca Mountain project
2012	Blue Ribbon Commission on America's Nuclear Future completes its recommendations, including a call for a consent-based process to identify alternative storage and disposal sites
2013	Federal Court of Appeals orders Nuclear Regulatory Commission (NRC) to complete its staff review of the Yucca Mountain application with remaining funds
2015	NRC staff completes Yucca Mountain review, finds that "the DOE has demonstrated compliance with the NRC regulatory requirements" for both preclosure and postclosure safety
2015	DOE begins consideration of a separate repository for defense high-level wastes and initiates first phase of public interactions planning for a consent-based siting process for both storage and disposal facilities. (Both activities terminated in 2017.)
2016-18	Private sector applications to the NRC for consolidated interim storage (Waste Control Specialists [now Interim Storage Partners] in Andrews, TX and Holtec in Eddy/Lea Counties, NM)
2020	Yucca Mountain licensing process remains suspended, and approximately 300 technical contentions remain to be heard before a licensing board can reach a decision

Some Open Questions and R&D

- Engineered barrier system materials
  - Understanding their behavior at high temperature and pressure over geologic time scales
  - Understanding radionuclide transport through them
  - Engineering materials with better heat transfer characteristics
- Postclosure criticality
  - Addition of filler material to waste packages containing SNF prior to disposal to prevent postclosure criticality
  - Understanding and quantifying consequences of a postclosure critical event
  - Development of advanced neutron absorbers for use in purpose-built waste packages
- Current “problematic” wastes in terms of disposal
  - Salt from Molten Salt Reactor Experiment
  - Salt from reprocessing Na-bonded spent fuel
  - Calcine waste

Conclusions

- Identified Characteristics of Waste to be Considered for Disposal Strategy
- Inventory
  - Long-term dose estimates in most geologic settings are dominated by mobile species, primarily I-129
  - Other major contributors to long-term dose are long-lived fission and activation products, and Ra-226, Pu-242, Np-237
- Volume and Thermal Power
  - Waste volume and thermal power density are, to a first approximation, inversely related
  - Without separation and surface aging of fission products for a century or more, reductions in disposal volume may be limited to 30-40% of the disposal volume of the unprocessed fuel
  - Fission products may need geologic disposal regardless, depending on regulatory criteria
- Waste Form Durability
  - Impact of long-lived waste forms on repository performance varies with disposal concept
  - For some disposal concepts, long-lived waste forms can be important

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